

# Stellar Archaeology: a Keck Pilot Program on Extremely Metal-Poor Stars From the Hamburg/ESO Survey. I Stellar Parameters<sup>1</sup>

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## ABSTRACT

In this series of two papers we present a high dispersion spectroscopic analysis of 8 candidate extremely metal poor stars selected from the Hamburg/ESO Survey and of 6 additional very metal poor stars. We demonstrate that with suitable vetting using moderate-resolution spectra the yield of this survey for stars with  $[\text{Fe}/\text{H}] \leq -3.0$  dex is very high; three out of the eight stars observed thus far at high resolution from the HES are actually that metal poor, three more have  $[\text{Fe}/\text{H}] \leq -2.8$  dex, and the remainder are only slightly more metal rich. In preparation for a large scale effort to mine the Hamburg/ESO Survey database for such stars about to get underway, we lay out in this paper the basic principles we intend to use to determine in a uniform way the stellar parameters  $T_{\text{eff}}$ ,  $\log(g)$ , and reddening.

*Subject headings:* Galaxy: halo — stars: abundances — Galaxy, evolution

## 1. Introduction

The most metal deficient stars in the Galaxy provide crucial evidence on the early epoch of the formation of our Galaxy, the chemical evolution of the Galaxy, the environment in which various elements were produced, the production of elements in the Big Bang, the age of the Galaxy, the relationship between the halo field stars and the galactic globular clusters, etc. We consider only stars with  $[\text{Fe}/\text{H}] \leq -3$  dex ( $<1/1000$  of the solar metallicity) to be extremely metal

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poor (henceforth EMP) and most useful for discussion of such issues. These EMP stars provide us with an opportunity to study in detail the local equivalent of the high redshift Universe.

The major existing survey for very metal poor stars is the HK survey (previously referred to as the Preston-Shectman survey) described in detail by Beers, Preston & Shectman (1985, 1992). This survey produced a list of  $\sim 10,000$  candidates for metal poor stars. Extensive follow up studies, which continue to this date, now include moderate-resolution ( $\Delta(\lambda) \sim 1 - 2\text{\AA}$ ) spectroscopy of about 5000 stars and broad- and narrow-band photometry for some 3000 stars. From this work one can cull a sample of roughly 1000 stars with  $[\text{Fe}/\text{H}] \leq -2.0$ , but, as summarized by Beers (1999), only roughly 100 are known to be extremely metal poor. High-dispersion analyses exist for only a few stars with  $[\text{Fe}/\text{H}] \leq -3.5$ , and the signal to noise ratio of these spectra are in general modest ( $\sim 30$  to  $40$ ), a situation which only very recently has been partially remedied for five giants through the work of Norris, Ryan & Beers (2001), and for the most metal-poor dwarf presently known, CS 22876-032 (Norris, Beers & Ryan 2000).

McWilliam (1997) reviews the key results from abundance analyses for the most metal poor stars known from the HK survey. The elements Al, Sr, Ba, Cr, Mn, Co show a sudden change in the slope of  $[\text{X}/\text{Fe}]$  versus  $[\text{Fe}/\text{H}]$  near  $[\text{Fe}/\text{H}] = -2.4$  dex. Other elements, including Ba and Sr, appear to show considerable scatter from star-to-star at very low  $[\text{Fe}/\text{H}]$ , perhaps indicating that the yield from individual or at most a few supernova events produced the metals seen in these EMP stars. However, the total sample of stars involved is 33 in the McWilliam *et al.* (1995) study and 19 in Ryan *et al.* (1996), with some overlap between these two samples, and many of these do not fit the strict definition of EMP stars adopted here.

The large scatter in the element-to-element abundance ratios observed amongst EMP stars might reveal a wealth of data for nucleosynthesis. However, a proper understanding of this scatter requires large samples. Furthermore, interesting new types of stars such as those extremely rich in r-process elements (useful for nucleocosmochronology) or extreme CH-stars (used to study the s-process) have been found based on the HK survey, but the number known in either case is very small, and urgently needs augmentation.

The Hamburg/ESO survey (HES) is an objective prism survey primarily targeting bright quasars (Wisotzki *et al.* 1996, 2000). However, because its spectral resolution is typically  $15\text{\AA}$  FWHM at  $\text{H}\gamma$ , it is also possible to efficiently select a variety of interesting *stellar* objects in the HES (Christlieb 2000; Christlieb *et al.* 2001a,b), among them EMP stars. The HES is based on automated scans of objective prism plates. With a nominal area of  $9,575\text{ deg}^2$ , it covers the entire southern extragalactic sky ( $|b| \geq 30\text{ deg}$ , and  $\delta < +2.5\text{ deg}$ ). The HES limiting magnitude for metal-poor stars is  $B \sim 17.5$ . The survey is now completed and the HES database contains digitized objective prism spectra for about 4 million stars.

A comparison of the EMP stars likely to be found with this survey as compared with the HK survey is given in Christlieb & Beers (2000). The HES has a number of crucial advantages over the HK survey which should lead to a major increase in the samples of EMP stars and hence,

with suitable follow up observations, in our knowledge of their properties. The advantages of the HES include a deeper magnitude limit, broader spectral coverage, and an automated selection from digitized scans of the plates. The latter ensures a selection of EMP stars which can be independent of stellar effective temperature.

The existence of a new list of candidates for EMP stars with  $[\text{Fe}/\text{H}] < -3$  dex selected in an automated and unbiased manner from the HES, coupled with the very large collection area and efficient high resolution Echelle spectrographs of 8–10 m telescopes such as Keck+HIRES or VLT+UVES, offers the possibility for a very large increase in the number of EMP stars known and in our understanding of their properties. The present pair of papers (this paper and Paper II, Carretta *et al.* 2001) describes our very successful pilot project with HIRES at the Keck Observatory in the fall of 2000 to determine the effective yield of the HES for EMP stars through high dispersion abundance analyses of a sample of stars selected from the HES. Our work complements and extends that of Depagne, Hill, Christlieb & Primas (2000), who analyzed two stars from the HES as part of the UVES science verification at the VLT.

This success has provided the stimulus for the creation of a long term large scale international effort to mine the HES for EMP stars (the OZ Project), which is now getting underway, and which will complement the efforts of the ESO-VLT large program led by Cayrel (see, e.g. Cayrel *et al.* 2001) dedicated to studying the HK survey stars themselves in more detail. In this pair of papers we strive to lay down at least some of the procedures that we will follow in our long term effort, whose goal is to dramatically increase the sample of known and well studied EMP stars. This first paper dedicated to determination of the stellar parameters.

## 2. The Sample of Stars Observed

Selection of EMP stars in the HES is carried by automatic spectral classification, using classical statistical methods (Christlieb 2000). As described in Christlieb *et al.* (2001a),  $B - V$  colors can be estimated directly from the digital HES spectra with an accuracy of  $\sim 0.1$  mag, so that these samples can be selected not only on the basis of spectroscopic criteria but also with restrictions on  $B - V$  color.

The principal spectroscopic criterion used for sample selection for EMP stars is the same as that used by the HK project, the absence/weakness of the 3933 Å line of Ca II. A visual check of the HES spectrum is then made to eliminate the small fraction of spurious objects (plate defects, misidentifications, etc.) that pass the automatic selection criteria. The details of this procedure will be discussed elsewhere (Christlieb *et al.* in preparation).

The results from follow-up observations of several hundred metal-poor candidates from the HES will be described elsewhere (Christlieb *et al.* in preparation). Here we only note that in the HES a very high selection efficiency for metal-poor stars has been achieved:  $\sim 60\%$  of the candidate EMP turnoff stars observed at moderate-resolution were confirmed to have

$[\text{Fe}/\text{H}] < -2.0$ , compared to  $\sim 30\%$  in the HK survey (Beers 2000). For the cooler giants, having a stronger Ca K line at given metallicity than turnoff stars, we expect the selection efficiency to be even higher due to the still detectable Ca K line at very low metallicities. This is currently under investigation.

The present sample was selected from the HES database to have  $0.3 < B - V < 0.5$  to focus on main sequence turnoff stars. The pool of candidates in the turnoff region consists of those stars whose line strengths are below the limit of detection for the HES. This limit corresponds to a metallicity which exceeds the upper limit adopted here for EMP stars, and hence the initial samples are dominated by stars that are very metal poor, but more metal rich than those we seek. Thus, to make the best use of the limited observing time available on the largest telescopes, these candidates from the HES database must first be verified through moderate-resolution ( $\sim 1\text{--}2\text{ \AA}$ ) follow-up spectroscopy at 4-m class telescopes. This procedure selects out the genuine EMP stars from the much more numerous stars of slightly higher metallicity – of interest in their own right – but not relevant for our present study. It is the overall efficiency of this multi-stage selection process for isolating genuine EMP stars which we seek to establish with our pilot project.

### 3. HIRES Observations

Once the list of vetted candidates for EMP candidates from the HES database has been created, observations at high dispersion for a full scale abundance analysis can be undertaken.

The sample of stars studied here includes seven previously vetted EMP main-sequence turnoff candidates and one giant candidate from the HES. Their coordinates are given in Table 1. One of these turned out to be a re-discovery of a star from the HK Survey (HE 2344–2800 = CS 22966–048). For comparison and calibration, three bright, well-studied very metal-poor stars were observed, two of which (G139-8 and BD+3 740) are known to be Li-deficient from the work of Norris, Ryan & Beers (2000). Three candidate EMP stars from the HK survey were also included. Observations were carried out with the HIRES spectrograph at Keck I on two nights in September 2000. A spectral resolution of 45,000 was achieved using a 0.86 arcsec wide slit projecting to 3 pixels in the HIRES focal plane CCD detector. The spectra cover the region from 3870 to 5400  $\text{\AA}$  with essentially no gaps. Each exposure for the HES stars was broken up into 1200 sec segments. The spectra were exposed until a SNR of 100 per spectral resolution element in the continuum at 4500  $\text{\AA}$  was achieved. This SNR calculation utilizes only Poisson statistics, ignoring issues of cosmic ray removal, night sky subtraction, flattening, etc. The observations were carried out with the instrument rotator fixed in the vertical position with respect to the horizon (i.e. at the parallactic angle). As suitable candidates are quite far apart on the sky compared to the 11 arcsec long slit, only a single object can be observed at once.

The exposure times and signal to noise ratios per spectral resolution element in the continuum are given in Table 2. (The gain setting of the HIRES CCD detector is  $2.4\text{ e}^-/\text{ADU}$ ; to reach the

desired SNR of 100 per spectral resolution element requires 1390 ADU/pixel.) These spectra were taken during a period when the Keck I mirror segments had not been aluminized for more than two years, and the overall throughput at these blue wavelengths needed improvement.

The spectra from both nights were reduced using the suite of routines for analyzing Echelle spectra written by McCarthy (1988) within the Figaro image processing package (Shortridge 1988). The stellar data are flat fielded with quartz lamp spectra, thereby removing most of the blaze profile, and the results are normalized to unity by fitting a 6th-order polynomial to line-free regions of the spectrum in each order.

Figures 1 and 2 show sections of the spectra for six of the stars, including the faintest star in our sample, a EMP main sequence turnoff star with easily detectable absorption in the G band of CH, and a newly discovered double-lined spectroscopic binary. The first panel shows the order containing the G band; the strongest two atomic absorption features in this order are the Fe I lines at 4271.8 and 4307.9 Å. In the second figure, the order containing the Sr II line at 4215.5 Å is shown; the strongest absorption line in that order is that of Ca I at 4226.7 Å. To facilitate a visual comparison of the relative strength of the Sr II line to other absorption lines, the spectra have been shifted in wavelength so as to remove the differences in radial velocity between the stars displayed in the figure. (The values of  $v_r$  are given in Table 7.)

The strong variation of the Sr II line relative to adjacent features is obvious. This variation is a well known characteristic of the spectra of metal poor stars (e.g. Ryan, Norris & Bessell 1991) and will be discussed at length in Paper II.

HE 0024–2523, in addition to showing the strongest CH band, also has absorption lines that are resolved, as is clearly shown in Figures 1 and 2. The most likely explanation for this is rotation. If so, this star has a rotational velocity of  $\sim 8$  km s $^{-1}$ . This star will be discussed again in Paper II and also in more detail in Gratton *et al.* (in preparation).

#### 4. Stellar Broad Band Photometry

*UBV* photometry for all the HES stars was obtained at the ESO-Danish 1.54 m telescope in November, using DFOSC (Beers *et al.*, in preparation). A  $1\sigma$  error of 0.02 mag was assumed for all optical colors. For BS 17447–029, *UBV* was available from Bonifacio, Monai & Beers (2000), but this disagreed badly with the *V* photometry from Anthony-Twarog *et al.* (2000). Because of this large discrepancy, *BV* for this star was re-observed at the 1.5-m telescope at Palomar Mountain. The result, given in Table 2, was identical to that of Anthony-Twarog *et al.*. Each of the remaining two stars from the HK survey had two independent sets of optical photometry from either Preston *et al.* (1991), Anthony-Twarog *et al.*, or McWilliam *et al.* (1995). These were in good agreement and the mean was used. For the three very bright calibrating stars, *UBV* was taken from the Mermilliod, Hauck & Mermilliod (1997) on-line data base.

We are very fortunate that uniform and reasonably precise broad band infrared photometry at  $JHK$ , crucial for determination of accurate values of  $T_{\text{eff}}$ , is now available for all our sample stars from the interim release of the 2MASS near infrared all-sky survey (Skrutskie *et al.* 1997). The global photometric calibration of this survey is discussed in Nikolaev *et al.* (2000). We adopt the photometric uncertainties given in the 2MASS catalog. For the bright calibration stars, the near-infrared photometry is from the most recent sources in the compilation of Gezari *et al.* (1999), specifically Arribas & Roger (1987), Laird, Carney & Latham (1988) and Alonso, Arribas & Martinez-Roger (1994). The photometry is collected in Table 2.

The HES stars are bright enough that preliminary proper motions for most of the HES stars are now available through the USNO CCD Astrograph Catalog (Zacharias *et al.* 2000) for the southern sky, with proper motions for the northern stars in the HES to follow in due course from this same astrometric program. Radial velocities for each EMP candidate from the HES will be obtained as large scale vetting using moderate-resolution spectroscopy proceeds over the next few years. Thus the full 3d velocity vector can be specified for *all* of the HES metal poor stars. Such a large non-kinematically selected sample of halo stars will be useful to compare with increasingly sophisticated models of the formation and evolution of the Milky Way, such as those of Chiba & Beers (2001) and references therein. A first attempt at such a comparison has been presented by Bekki & Chiba (2001).

Throughout this paper we use the new  $Y^2$  isochrones of Yi *et al.* (2001), which are calculated for a scaled solar mixture. We adopt an age of 12 Gyr,  $[\text{Fe}/\text{H}] = -3.3$  dex, with  $Y = 0.230$ , as the parameters of our standard isochrone. Because the metallicity of our stars are so low, the details of the treatment of the opacities are not critical, and there is reasonably good agreement with isochrones computed using older stellar evolutionary codes such as those of Bergbusch & Vandenberg (1992). We will find later that the same statement holds true for model atmospheres, for similar reasons.

## 5. Interstellar Reddening

A precise measurement of the reddening is crucial for the derivation of accurate stellar parameters from broad band photometry. Even adding the infrared does not help much if the reddening is poorly determined in this  $T_{\text{eff}}$  regime. As is shown in Table 4, to be discussed in detail later, the enhanced sensitivity to small changes in  $T_{\text{eff}}$  one gains by moving to optical+near-IR colors such as  $V - K$  is accompanied by an enhanced sensitivity to reddening errors. In a project such as mining the HES for EMP stars, where many stars separated by large solid angles on the sky are involved, control of the uniformity of the reddening estimates is mandatory.

We adopt the extinction maps of Schlegel, Finkbeiner & Davis (1998) from their analysis of the COBE/DIRBE database. The relative extinction in various passbands is taken from Cohen *et al.* (1981) (see also Schlegel, Finkbeiner & Davis 1998).

The HES includes only high galactic latitude fields within which  $E(B - V)$  is almost always  $\leq 0.10$  mag. Hence, although there is some concern that the magnitude of the Schlegel *et al.* extinction corrections may be slightly too large, particularly in regions where the extinction is high ( $E(B - V) > 0.15$ , see, e.g. Acre & Goodman 1999), we adopt these values without further discussion or amendment.

All of the HES stars are fainter than  $V \sim 14$  as saturation effects within the photographic plates used for the survey become important for brighter objects. Given their high galactic latitude, these stars are sufficiently distant, even if they are main sequence turnoff stars rather than giants, that they can all be assumed to be beyond the reddening layer, whose thickness  $H$  is only  $\sim 200$  pc (see the review of Dickey & Lockman 1990). Therefore the full extinction is applied to each of them.

The reddening for the brightest calibrating star (HD 140283) is assumed to be 0.00. This star is only about 60 pc away, and has a Hipparcos parallax. The other two calibrating stars and the three stars from the HK Survey in the present sample are not so distant as to be beyond the reddening layer, and yet not so close that reddening can be ignored. We therefore use an iterative scheme of estimating the reddening, calculating  $T_{\text{eff}}$  (see below), computing the distance  $D$  using the luminosity from the stellar evolutionary tracks of Yi *et al.* (2001), and then checking the estimate of the reddening against the quantity  $E(B - V) \times e^{-D \sin(b)/H}$ . Similar schemes are described by Laird, Carney & Latham (1988) and by Bonifacio *et al.* (2000). Rapid convergence for  $E(B - V)$  is obtained.

The recommended values of  $E(B - V)$  are given in the last column of Table 2. The reddenings for the HES stars are quite small, with all but one of our sample having  $E(B - V) < 0.03$  mag. It is only for the brighter calibration objects that this issue becomes a major concern.

## 6. $T_{\text{eff}}$ from Broad Band Colors

Because of concerns about potential non-LTE effects, which are suspected to be stronger in very metal poor stars than in stars of solar metallicity, we must derive  $T_{\text{eff}}$  from broad band colors. Detailed calculations for non-LTE in Fe are presented in Thévenin & Idiart (1999) and in Gratton *et al.* (1999). Although the most careful analyses of globular cluster and field stars of higher metallicity than those considered here, such as that of Cohen, Behr & Briley (2001) and Ramírez *et al.* (2001) for a large sample of stars over a wide range in luminosity in M71, Ivans *et al.* (2001) for a large sample of red giants in M5, or Allende Prieto, Asplund, Garcia Lopez & Lambert (2002) for Procyon, show that departures from LTE in the formation of Fe lines are relatively small, the predicted strength of the departures from non-LTE increases as the metallicity decreases. To be conservative, at least initially, measurements based on ionization equilibrium in the spectra themselves cannot be considered as reliable at this time.

We utilize here the grid of predicted broad band colors and bolometric corrections of

Houdashelt, Bell & Sweigart (2000) based on the MARCS stellar atmosphere code (Gustafsson *et al.* 1975). We assume that their Johnson-Glass  $J, K$  colors are equivalent to the  $J, K_s$  2MASS colors. Carpenter (2001) has derived the transformations between the 2MASS photometric system and many other infrared photometric systems, and finds a very small zero point offset between these two infrared photometric systems, which we have chosen to ignore until the final release of the 2MASS catalog becomes available.

Cohen, Behr & Briley (2001) have demonstrated that the Kurucz and MARCS predicted  $V - K$  colors are essentially identical, at least for  $V - K$  colors and for the set of models with  $[\text{Fe}/\text{H}] = -0.5$  dex.

Since we are interested in EMP stars, the details of the treatment of the opacity from any element other than H should not be important, and we expect to continue to find very good agreement for the predicted broad band colors from the various grids of model atmospheres available. In our tests, we take the predicted  $V - K$  color from each model in the MARCS grid with  $[\text{Fe}/\text{H}] = -3.0$ , and interpolate within the Kurucz color grid at the same abundance and at the  $\log(g)$  of the MARCS model to find the  $T_{\text{eff}}$  that would be deduced. We continue this comparison, checking  $V - K$ ,  $V - J$  and  $B - V$  at  $[\text{Fe}/\text{H}] = -3.0$  dex. We find that the colors predicted from the MARCS code from Houdashelt *et al.* are essentially identical to those from the Kurucz ATLAS code (Kurucz 1992) at this low metallicity.

A contour plot of the difference  $\Delta T_{\text{eff}}(\text{Kurucz} - \text{MARCS})$  that results when the  $V - J$  color is used is shown in Figure 3. The four contour levels displayed correspond to  $\Delta T_{\text{eff}} = -30, -10, 10$  and  $30$  K. Also shown in this figure as the thick curve is a 12 Gyr isochrone for  $\text{Fe}/\text{H} = -2.3$  dex from the very recently completed  $Y^2$  isochrones of Yi *et al.* (2001). Along this isochrone,  $\Delta T_{\text{eff}} = 0$  to  $30$  K for the subgiants and main sequence turnoff region, and  $\Delta T_{\text{eff}} = 0$  to  $-30$  K for the red giant branch. We thus demonstrate that, to within a tolerance of  $\pm 30$  K, the Kurucz and MARCS temperature scales from broad band  $V - J$  colors are identical.

We therefore proceed to assign values of  $T_{\text{eff}}$  using the grid of colors of Houdashelt *et al.* (2000). For the calibrating stars and for some of the brighter stars from the HK survey, a high dispersion abundance analysis has already been done. These are summarized in Table 3. In these cases we take the  $[\text{Fe}/\text{H}]$  from such an analysis as our initial guess for the stellar metallicity. If not, we assume  $[\text{Fe}/\text{H}] = -3.0$  dex. We adopt initial guesses for  $\log(g)$  based on whether the star is a giant or a main sequence turnoff star. These rough guesses are used to interpolate to the proper value in the desired color, which depends slightly on  $\log(g)$  and abundance, as well as on  $T_{\text{eff}}$ .

This process is illustrated for a subgiant and for a main sequence turnoff region star (the faintest star in the present sample) in Figure 4. The results for three colors,  $B - V$ ,  $V - J$  and  $V - K$ , are shown as solid curves, with the thickness of the curves varying,  $B - V$  having the thinnest and  $V - K$  having the thickest curves. Dashed curves denote the  $T_{\text{eff}}$  deduced for the observed and dereddened colors  $\pm$  the  $1\sigma$  uncertainty of each observation. In a perfect world, all the solid curves would overlap to within the uncertainties at some definite value of  $T_{\text{eff}}$ , and this



does in fact occur for the stars shown in the figure. We have found that the  $B - V$  colors give systematically higher  $T_{\text{eff}}$ , by about 50 K, for the main sequence EMP stars (see Figure 4).

Table 4 gives the sensitivity of each color to various stellar parameters. These are expressed as the change in the parameter (which may be positive or negative) that would result from a  $+1\sigma$  change in the color, where the observational uncertainty for each color defines the value of  $\sigma$  used. These calculations were made using stellar parameters appropriate for EMP main sequence turnoff stars. We infer from this table, for example, that  $B - V$  is less sensitive to changes in  $T_{\text{eff}}$  than either  $V - J$  or  $V - K$ , and that none of the colors considered is capable of applying a significant constraint on the metallicity of a star.

The values of  $T_{\text{eff}}$  that result from this procedure, applied to each star in our sample, are listed in Table 5. As one might expect from Table 4, they have typical internal errors of  $\pm 75$  K, except for those from  $B - V$ , where the error is  $\sim \pm 125$  K.

$U - B$  colors are also available, but they are more difficult to match to the predictions of the model atmosphere grid. For five of the eight stars from the HES,  $U - B < -0.25$  mag when corrected for reddening. This is very blue, so much so that such a blue color is not reached in the relevant regime of  $T_{\text{eff}}$  and  $\log(g)$ , even at  $[\text{Fe}/\text{H}] = -3.0$  dex, the most metal poor models in the grid of Houdashelt *et al.* (2000). In addition, the predictions for  $U - B$  depend sensitively on metallicity as well as  $T_{\text{eff}}$  and  $\log(g)$ , and are non-monotonic in these two parameters.

While the contribution from line opacities becomes less important in defining continuum fluxes at the lowest metallicities, some problems in the violet and ultraviolet may remain. We believe that these problems of properly predicting the flux in the region 3500 – 4500 Å in these EMP stars are related to the extremely low metallicity of these stars, to the sensitivity to multiple parameters, and to the relatively small sensitivity to  $T_{\text{eff}}$ . This situation is alleviated by using redder colors with wider wavelength separation. Therefore the adopted  $T_{\text{eff}}$  given in Table 5 are the means of those deduced from the dereddened  $V - J$  and the  $V - K$  colors.

We have also determined  $T_{\text{eff}}$  through examination of the Balmer line profiles.  $\text{H}\alpha$  is the Balmer line best suited for this purpose, because it has the strongest temperature sensitivity, and its profile is almost independent of the choice of the mixing-length parameter  $\alpha$  (e.g., Fuhrmann *et al.* 1993). Unfortunately,  $\text{H}\alpha$  is not covered by the spectral range chosen in this work.  $\text{H}\beta$  is not well centered in the echelle orders, hence unsuitable. The continuum near  $\text{H}\gamma$  may be perturbed by strong CH lines in carbon-enhanced stars, which occur at rate of  $\sim 20\%$  among EMP stars. Hence we utilize  $\text{H}\delta$  for this purpose. A special reduction of the relevant order was made to ensure the best possible continuum level. The orders above and below this were used as necessary to interpolate the continuum level across the Balmer line. The synthetic Balmer line profiles computed by the Gehren group (Fuhrmann 1998, 2000 private communication) are used. The results are listed in the fifth column of Table 5. These have a typical error of  $\pm 100$  K.

A perusal of Table 5 shows that we have achieved consistency to within  $\pm 100\text{K}$  between the  $T_{\text{eff}}$  from the Balmer line profile and from the broad band colors, as is also shown in Figure 5.

The solid line denotes equality between the  $T_{\text{eff}}$  from the broad band photometry and from the  $H\delta$  profiles, while the dashed line is the best linear fit excluding the single subgiant, which suggests that the  $T_{\text{eff}}$  for the turnoff stars from the broad band photometry is systematically slightly hotter than that inferred from  $H\delta$ .

We note that the  $T_{\text{eff}}$  we assign to these main sequence turnoff stars is identical to that found through stellar evolution, i.e. the predicted location of the main sequence turnoff in 12 Gyr isochrones for metal poor stars, which is at about 6600 K for  $[\text{Fe}/\text{H}] = -2.3$  and about 6750 K for  $[\text{Fe}/\text{H}] = -3.3$  dex. If the  $T_{\text{eff}}$  we assign are consistent with the  $T_{\text{eff}}$  scale adopted for the  $Y^2$  grid of isochrones, ages older than 14 Gyr can be ruled as the main sequence turnoff then becomes cooler than the observed values reached by these stars. Such old ages are also not supported by recent Boomerang observations of the fluctuations in the CMB (de Bernardis *et al.* 2000).

### 6.1. Comparison With the Empirical $T_{\text{eff}}$ Scale of Alonso *et al.*

We have compared our  $T_{\text{eff}}$  scale with the empirical color– $T_{\text{eff}}$ – $[\text{Fe}/\text{H}]$  relations for dwarfs and for giants established by Alonso *et al.* (1996, 1999). We use their polynomial fit for the  $V - K$  colors, simulating moving down in luminosity along an isochrone from the tip of the RGB to the main sequence for EMP stars. Since the Alonso *et al.* fits are not well calibrated at extremely low metallicities, we use their fits with  $[\text{Fe}/\text{H}] = -2.0$  dex; the metallicity sensitivity of  $V - K$  at lower abundances than this is small.

We find that  $T_{\text{eff}}$  inferred from the Alonso *et al.* relations for the  $V - K$  color is 150 K cooler than that inferred from the Houdashelt *et al.* (2000) grid of colors predicted from stellar atmosphere models near the top of the giant branch, but this decreases to 100 K cooler for subgiants and for stars near the main sequence turnoff for  $[\text{Fe}/\text{H}] = -2.0$  dex. Pushing the Alonso *et al.* relations beyond their regime of validity and verification to  $[\text{Fe}/\text{H}] = -3.0$  dex would produce good agreement at the main sequence but the subgiants and giants would still be 100 K hotter using the MARCS color grid.<sup>6</sup> The Alonso scale thus is close to the  $T_{\text{eff}}$  determined from  $H\delta$ .

Thus, at least with respect to the  $V - K$  color, the Alonso *et al.* scale and our  $T_{\text{eff}}$  scale are in good agreement for turnoff stars. The small systematic difference of a maximum of 100 K for giants would translate into a change in derived metallicity of  $\Delta[\text{Fe}/\text{H}] \sim -0.1$  dex.

Because the Alonso *et al.* empirical  $T_{\text{eff}}$  scale is not calibrated for stars as metal poor as our sample, and because of our philosophical preference to utilize the same model atmospheres that one must rely upon for analyses of the spectral features, we have chosen to adopt the  $T_{\text{eff}}$  scale established from broad band optical-IR colors. One potential systematic error for this choice is the matching of the photometric systems between the observational colors and the theoretically

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<sup>6</sup>This may be related to problems encountered by Lebreton (2000) in matching stellar evolutionary isochrones with stellar parameters for nearby stars with Hipparcos parallaxes.

predicted ones. We believe that the internal errors in our adopted  $T_{\text{eff}}$  are  $\pm 75$  K, with a possible systematic overestimate (arising from as yet unknown causes) for the main sequence turnoff stars only of  $\sim 100$  K.

## 6.2. Comparison With Previous $T_{\text{eff}}$ Determinations

We compare our values of  $T_{\text{eff}}$  with the limited set of values available from previous analyses of the brighter stars in our sample. We adjust the  $T_{\text{eff}}$  values listed in Table 5 for the difference in reddening between the values we adopt given in Table 2 and those adopted in previous analyses. The results are given in Table 6. Once the reddenings are forced to the same value, each of the five entries has  $|\Delta(T_{\text{eff}})(\text{old} - \text{now})| < 100$  K. This is very encouraging.

## 7. Surface Gravities

The only broad band color among those available to us with strong sensitivity to  $\log(g)$  is  $U - B$ . However, for the reasons described in §6, we choose not to use it except in the crudest possible sense, i.e. to discriminate among turnoff stars and subgiants and giants. We cannot utilize the usual spectroscopic indicator, the ionization equilibrium, because of the possibility of non-LTE effects as described above.

Once  $T_{\text{eff}}$  is known, we determine  $\log(g)$  from the  $Y^2$  isochrone for stars that are 12 Gyr old with  $Z = 1.0 \times 10^{-5}$ , equivalent to  $[\text{Fe}/\text{H}] = -3.3$ . The  $\log(g)$  is determined directly from the isochrone using the  $T_{\text{eff}}$  of the star. If the 14 Gyr isochrone of the same metallicity from the  $Y^2$  grid were adopted, the assigned  $\log(g)$  would increase by an amount which is negligible for the main sequence stars and which increases as  $T_{\text{eff}}$  decreases, to 0.15 dex for  $T_{\text{eff}} = 5000$  K.

This procedure is not very precise for giants because the slope of the RGB is rather steep,  $\Delta(\log(g)/T_{\text{eff}}) = \sim 0.3$  dex/100 K. Consideration of the rate of evolution along the isochrone as a function of luminosity, which directly translates into the number density of stars along the isochrone, dictates that the probability of finding subgiants is considerably higher in faint samples such as the HES than that of finding stars well up the RGB.

For stars near the main sequence turnoff, which is the location of the bulk of the present sample, the slope of the isochrone is much shallower and good discrimination in  $\log(g)$  is possible.

However, there are two solutions in the isochrone for a fixed  $T_{\text{eff}}$  near the main sequence turnoff, one corresponding to main sequence stars slightly fainter than the turnoff, and one to stars which have just started to evolve off the main sequence toward the base of the giant branch; these two solutions differ by about 1 dex in  $\log g$  for  $T_{\text{eff}} \sim 5900$  K. For  $T_{\text{eff}}$  more than  $\sim 500$  K cooler than the turnoff itself, the lower luminosity of the main sequence stars makes their detection quite unlikely, even though their volume density is higher than the post-turnoff main sequence stars. In

fact, assuming a constant volume density over the galactic region sampled by HES <sup>7</sup>, a comparison with globular cluster luminosity functions show that at this temperature we expect to detect approximately one main sequence star out of 10 to 15 subgiants. For  $T_{\text{eff}}$  closer to the turnoff, both solutions have fairly similar probabilities, although the brighter (lower gravity) solution is always more probable.

We cannot distinguish between these two cases using our present photometric dataset alone. Making this distinction using the Fe ionization equilibrium (i.e. relying on the spectra, and on the understanding of or absence of large non-LTE effects) is only feasible in the best of our spectra as the difference in  $\log(g)$  between the two solutions is not large. As noted in Table 5, the detailed analysis of the spectra presented in Paper II suggests that two of the three bright comparison stars near the main sequence turnoff actually are slightly fainter than the turnoff. All of the HES sample members have been assigned to be brighter than the main sequence turnoff.

Only one of the stars among the bright calibration objects has an accurate Hipparcos parallax, HD 140283, discussed by Korn & Gehren (2000). We adopt their value of  $\log(g)$ . Our derived  $\log(g)$  for BD+3 740 is consistent with that inferred from the rather uncertain Hipparcos parallax for that star ( $7.8 \pm 2.1$  mas), assuming a mass of  $0.8 M_{\odot}$ .

We emphasize that our  $T_{\text{eff}}$  determination is independent of any spectroscopic criteria, and that the choice of  $\log(g)$  is made based on  $T_{\text{eff}}$  and an assumed isochrone. It is only when there are multiple possible values of  $\log(g)$  with approximately equal probability, which occurs only near the main sequence turnoff, that spectroscopic criteria are used. The difference in  $\log(g)$  between the two solutions does not exceed 0.5 dex before the lower luminosity solution becomes highly improbable. The details of abundance analyses to be presented in Paper II will verify the validity of this process.

## 8. Cautionary Notes

Kurucz (2001) has reviewed the many deficiencies of the current state of stellar astrophysics. The treatment of non-LTE in essentially all abundance analyses may be inadequate. (We only apply non-LTE corrections for a selected small set of ions. See Paper II.) Our treatment of convection surely could be better. Detailed three dimensional radiative-hydrodynamic convection simulations for solar granulation such as those of Asplund *et al.* (2000) now exist. The first steps towards utilizing such models (Allende-Prieto *et al.* 2002) to study line profiles and abundances are now starting to become available, although such an elegant treatment still requires large amounts of computing time and very high precision spectra, with much better spectral resolution and SNR than those discussed here.

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<sup>7</sup>Typical distances of turnoff-stars in the HES survey are  $\sim 1$  kpc; this is much less than the local value of the halo scale height.

In our present application, the question is how well does the continuum and its broad band colors, or the Balmer-line profiles, represent the temperature gradient within the atmosphere. This is what is explored by the absorption features, as strong lines tend to arise from levels with smaller excitation potentials, and hence are formed farther out in the atmosphere. Kurucz points out that Balmer line wings will be preferentially formed in the hotter convective elements due to the high excitation potential of the second level of H I. Hence a simple one dimensional model such as we are using will have a somewhat higher  $T_{\text{eff}}$  deduced from the Balmer lines than does the real star. However, with such metal poor stars, all the absorption lines are very weak, and the issue of the temperature gradient within the atmosphere is perhaps less critical, as the lines are formed closer to the mean depth of formation of the continuum.

$T_{\text{eff}}$  obtained from the excitation temperature of Fe should be reliable, and disagreements between these atmospheric parameters and those from  $T_{\text{exc}}$  might indicate problems with the correct temperature stratification in the atmosphere. Such problems have been noted in the past by Dalle Ore (1992) and by Gratton, Carretta & Castelli (1996), with a more limited discussion given in Fulbright (2000). These problems appear to be considerably worse in the very metal poor giants than in the dwarfs. This issue will be taken up again in the following paper.

We have adopted a prescription, based on photometric indices for determining the stellar parameters of our very metal poor stars, that is quite different from that used in most previous analyses, which rely much more on spectroscopic equilibria and/or exclusively on bluer colors. By rejecting the spectroscopic equilibria in choosing  $T_{\text{eff}}$ , and by using theoretical isochrones to determine  $\log(g)$ , we leave open the possibility that our derived Fe abundances may have a dependence on the lower excitation potential of the transition,  $\chi$ . This in fact turns out to be the case; we do find a small dependence in some stars in Paper II. The possible existence of this dependence means that care must be exercised in comparing our abundances with those from other analyses, as the distribution of line excitation potentials in the two samples must be taken into account.

## 9. The Yield of the HES for EMP Stars

In the last column of Table 7 we give the Fe abundance ( $[\text{Fe}/\text{H}]$  deduced from Fe I lines) for the present sample, taken from Paper II. For the bright stars with previous high dispersion abundance analyses, listed in Table 3, we find that our abundances are comparable when the  $T_{\text{eff}}$  values adopted in both analyses are essentially identical (see Table 6), and tend to be slightly higher in those cases where our adopted  $T_{\text{eff}}$  is hotter, as expected.

Three of the eight HES candidate EMP stars in the present sample do in fact have  $[\text{Fe}/\text{H}] \leq -3.0$  dex, with three others having  $[\text{Fe}/\text{H}] \leq -2.8$  dex. The sample of two very metal poor stars observed by Depagne *et al.* (2001) at the VLT also yielded metallicities close to those expected from their moderate-resolution follow up spectra. This means that the process of automatic

selection of EMP candidates from the HES, followed by a visual check, then further vetting using moderate-resolution spectroscopy, produces samples of EMP stars with a high yield.

It is interesting to compare our derived  $[\text{Fe}/\text{H}]$  values from the present set of HIRES spectra with the abundance inferred for the stars in our sample from the moderate-resolution follow up spectroscopy. Those values are deduced from the strengths of the Ca II absorption at 3933 Å, the Balmer lines, and the  $B - V$  colors with the standard method developed for the HK survey, and most recently described in Beers *et al.* (1999)<sup>8</sup>, and are given in the next to last column of Table 7, together with a  $1\sigma$  error on the abundance determination. The metallicities obtained from the moderate-resolution spectra are, in general, somewhat more metal-poor, part of which may arise from the somewhat hotter  $T_{\text{eff}}$  values adopted here. The difference in the mean  $[\text{Fe}/\text{H}]_K - [\text{Fe}/\text{H}]_{\text{HIRES}}$  is  $-0.23$  dex, with a dispersion about this mean offset of 0.32 dex. This dispersion is in accordance with expectation, given the listed errors in  $[\text{Fe}/\text{H}]_K$  and the smaller errors expected for the present effort. A detailed discussion of these moderate-resolution spectra and the derivation of metallicities therefrom will be given elsewhere (Christlieb *et al.* in preparation).

All of this is very encouraging for future large scale projects which plan to mine the HES database for extremely metal poor stars.

## 10. Summary

In this paper and its companion paper, which presents a detailed abundance analysis for these HIRES spectra, we have demonstrated the high effective yield of the HES for extremely metal poor stars, and we now intend to embark on a major project (the 0Z Project) to understand the early chemical evolution of the galactic halo.

Our ultimate goal, which will take perhaps five years to reach with several large observatories working in a coordinated fashion, is high dispersion abundance analyses of a sample of 500 extremely metal poor stars. We will gain a detailed knowledge of chemical evolution during the initial phases of the formation of the Galactic halo, the kinematic properties of the extremely metal poor halo stars, a much better knowledge of the metallicity distribution of very metal poor halo stars, a much better estimate for the metallicity of the most metal poor stars (currently  $[\text{Fe}/\text{H}] = -4.0$  dex). A detailed study of those extremely rare r-process enhanced stars that may be found similar to that of Cayrel *et al.* (2001) will improve our age estimates for the Galactic halo based on radioactive decays of unstable heavy elements.

The entire Keck/HIRES user community owes a huge debt to Jerry Nelson, Gerry Smith, Steve Vogt, and many other people who have worked to make the Keck Telescope and HIRES a

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<sup>8</sup>Some additional features, such as auto-correlation function measurements, were added to the standard abundance estimation algorithms for the HK Survey by Beers *et al.* (1999); those were not used for the HES stars.

reality and to operate and maintain the Keck Observatory. We are grateful to the W. M. Keck Foundation for the vision to fund the construction of the W. M. Keck Observatory. The authors wish to extend special thanks to those of Hawaiian ancestry on whose sacred mountain we are privileged to be guests. Without their generous hospitality, none of the observations presented herein would have been possible.

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Table 1. Coordinates for the HES Stars in the HIRES Sample

Name	<i>V</i> (mag)	RA (J2000)	Dec (J2000)
HE 2133–1426	15.484	21 36 07.2	–14 12 36
HE 2344–2800 <sup>a</sup>	14.856	23 46 44.4	–27 44 10
HE 0024–2523 <sup>b</sup>	14.913	00 27 27.6	–25 06 26
HE 0130–2303	14.758	01 33 18.2	–22 48 36
HE 0132–2439	14.821	01 34 58.8	–24 24 18
HE 0148–2611	14.453	01 50 59.5	–25 57 02
HE 0218–2738 <sup>c</sup>	14.883	02 21 04.0	–27 24 40
HE 0242–0732	15.793	02 45 00.6	–07 19 42

<sup>a</sup>This is a re-discovery of CS 22966–048, originally found in the HK survey.

<sup>b</sup>This star has easily detectable CH absorption in the G band and its lines are resolved.

<sup>c</sup>The HIRES spectra show this star is a double-lined spectroscopic binary.

Table 2. Observed Colors and Details of the HIRES Spectra for the Stellar Sample

Name	$V$ (mag)	$U - B$ (mag)	$B - V$ (mag)	$J$ (mag)	$K$ (mag)	Exp. Time (sec)	SNR <sup>a</sup> (at 4625 Å)	$E(B - V)$ (mag)
Very Bright								
HD 140283	7.211	−0.196	0.490	6.03	5.63	75	300	0.000
BD+3 740	9.808	−0.20	0.36	8.77	8.49	240	240	0.037
G139–8	11.508	−0.203	0.475	10.345	10.031	650	165	0.067
HK Stars								
BS 17447–029	13.57	−0.30	0.40	12.583	12.313	1800	113	0.047
CS 22878–101	13.78	0.299	0.799	11.87	11.26	3600	96	0.086
CS 22950–046	14.224	0.345	0.906	12.228	11.570	2400	93	0.108
HES Stars								
HE 2133–1426	15.484	−0.237	0.449	14.374	14.120	9900	105	0.052
HE 2344–2800 <sup>b</sup>	14.856	−0.191	0.388	13.930	13.763	9600	125	0.018
HE 0024–2523	14.913	−0.254	0.408	14.067	13.740	6000	98	0.017
HE 0130–2303	14.758	−0.225	0.393	13.901	13.554	6000	120	0.012
HE 0132–2439	14.821	−0.117	0.630	13.379	12.931	4800	90	0.012
HE 0148–2611	14.453	−0.250	0.371	13.545	13.291	3600	102	0.013
HE 0218–2738 <sup>c</sup>	14.883	−0.240	0.394	13.979	13.711	7200	115	0.013
HE 0242–0732	15.793	−0.271	0.434	14.795	14.567	9300	94	0.027

<sup>a</sup>SNR is given per spectral resolution element (3 pixels).

<sup>b</sup>This is a re-discovery of CS 22966–048, originally found in the HK survey.

<sup>c</sup>The HIRES spectra show this star is a double-lined spectroscopic binary.

Table 3. Recent High Dispersion Abundance Analyses of The Brighter Sample Stars

Name	$T_{\text{eff}}$ (K)	$\log(g)$ (dex)	[Fe/H] (dex)	$E(B - V)$ (mag)	Ref.
Very Bright					
HD 140283	5750	3.4	−2.54	0.01	a
	5680	3.5	−2.64	0.00	b
	5810	3.67	−2.29	... <sup>h</sup>	c
	5650	3.4	−2.4	... <sup>i</sup>	d
BD+3 740	6240	4 <sup>j</sup>	−2.70	0.01	e
	6075	3.8	−2.7	... <sup>i</sup>	d
G139−8	6025	4 <sup>j</sup>	−2.56	0.04	f
HK Stars					
CS 22878−101	4780	1.15	−3.13	0.06	g
CS 22950−046	4635	0.85	−3.40	0.06	g

<sup>a</sup>Ryan, Norris & Beers (1996)

<sup>b</sup>Nissen *et al.* (1994) and Edvardsson *et al.* (1994)

<sup>c</sup>Korn & Gehren (2000) – using  $\log(g)$  from Hipparcos parallax

<sup>d</sup>Fulbright (2000)

<sup>e</sup>Ryan, Norris & Beers (2000)

<sup>f</sup>Norris, Ryan, Beers & Deliyannis (1997)

<sup>g</sup>McWilliam, Preston, Sneden & Searle (1995)

<sup>h</sup> $T_{\text{eff}}$  based on analysis of Balmer line profiles.

<sup>i</sup> $T_{\text{eff}}$  is deduced from the Fe spectrum.

<sup>j</sup>Star assumed to be at/near main sequence turnoff.

Table 4. Sensitivity of the Various Colors for EMP Turnoff Stars

Color	$1\sigma^{\text{a}}$ (mag)	$\delta(T_{\text{eff}})^{\text{b}}$ (K)	$\delta(\log(g))^{\text{b}}$ (dex)	$\delta([\text{Fe}/\text{H}])^{\text{b}}$ (dex)	$\delta[E(B - V)]^{\text{b}}$ (mag)
$B - V$	0.02	−125	+1.4	> 2.0	+0.020
$V - J$	0.03	−71	+1.7	> 2.0	+0.014
$V - K$	0.04	−73	+1.7	> 2.0	+0.015

<sup>a</sup>These are typical  $1\sigma$  observational errors.

<sup>b</sup>Change in the stellar parameter for a  $+1\sigma$  change in the color.

Table 5. Stellar Parameters for the Stellar Sample

Name	$T_{\text{eff}}(B - V)$ (K)	$T_{\text{eff}}(V - J)$ (K)	$T_{\text{eff}}(V - K)$ (K)	$T_{\text{eff}}(\text{H}\delta)$ (K)	$T_{\text{eff}}(\text{adopt})^{\text{a}}$ (dex)	$\log(g)$
Very Bright						
HD 140283	5935	5710	5785	5800	5750	3.67
BD+3 740	6750	6260	6450	6400	6355	4.0
G139–8	6500	6105	6290	6200	6200	4.5 <sup>e</sup>
HK Stars						
BS 17447–029	6800	6470	6570	...	6530	4.4 <sup>e</sup>
CS 22878–101	4870	4735	4820	... <sup>c</sup>	4775	2.3
CS 22950–046	4870	4695	4770	... <sup>c</sup>	4730	2.3
HES Stars						
HE 2133–1426	6475	6145	6460	6300	6300	4.1
HE 2344–2800 <sup>b</sup>	6700	6500	6750	6400	6625	4.3
HE 0024–2523	6550	6700	6550	6500	6625	4.3
HE 0130–2303	6600	6600	6525	6500	6560	4.3
HE 0132–2439	5440	5250	5375	5400	5310	3.4
HE 0148–2611	6800	6500	6600	6500	6550	4.3
HE 0218–2738 <sup>d</sup>	6625	6500	6600	6400	6550	4.3
HE 0242–0732	6550	6360	6550 <sup>f</sup>	6200	6455	4.2

<sup>a</sup>The adopted  $T_{\text{eff}}$  is a mean of that derived from the dereddened  $V - J$  and  $V - K$  colors. See text.

<sup>b</sup>This is a re-discovery of CS 22966–048, originally found in the HK survey.

<sup>c</sup>Star is too cool to show Balmer line wings.

<sup>d</sup>The HIRES spectra show this star is a spectroscopic binary.

<sup>e</sup>The lower luminosity solution is chosen, so the star is fainter than the main sequence turnoff. See text.

<sup>f</sup>The uncertainty in the 2MASS  $K$  mag is unusually large,  $1\sigma = 0.10$  mag.

Table 6. Comparison of  $T_{\text{eff}}$  Determinations

Name	$T_{\text{eff}}$ (K)	$E(B - V)$ (mag)	Ref.	$T_{\text{eff}}$ (Table 3) (K)	$T_{\text{eff}}$ (Table 3 With Previous $E(B - V)$ ) <sup>a</sup>
Very Bright					
HD 140283	5680–5810	0.01	b,c,d, e	5750	5785
BD+3 740	6240	0.01	f	6355	6260
G139–8	6025	0.04	g	6200	6105
HK Stars					
CS 22878–0101	4780	0.06	h	4775	4730
CS 22950–0046	4635	0.06	h	4730	4620

<sup>a</sup>Here we derive  $T_{\text{eff}}$  using our photometry and calibrations but adopt the reddening value used in the previous abundance determination.

<sup>b</sup>Ryan, Norris & Beers (1996)

<sup>c</sup>Nissen *et al.* (1994) and Edvardsson *et al.* (1994)

<sup>d</sup>Korn & Gehren (2000) – using  $\log(g)$  from Hipparcos parallax

<sup>e</sup>Fullbright (2000)

<sup>f</sup>Ryan, Norris & Beers (2000)

<sup>g</sup>Norris, Ryan, Beers & Deliyannis (1997)

<sup>h</sup>McWilliam, Preston, Sneden & Searle (1995)

Table 7. Spectroscopic Parameters for the Stellar Sample

Name	$v_r^f$ (km s <sup>-1</sup> )	[Fe/H](K) <sup>a</sup> (dex)	[Fe/H] (HIRES) <sup>b</sup> (dex)
Very Bright			
HD 140283	-171.0 <sup>c</sup>	...	-2.43
BD+3 740	+174.5	...	-2.69
G139-8	-114.0	...	-2.04
HK Stars			
BS 17447-029	-205.0	-3.15(0.26)	-2.91
CS 22878-101	-131.7	-2.91(0.18)	-3.04
CS 22950-046	+106.7	-3.63(0.15)	-3.28
HES Stars			
HE 2133-1426	+19.6	-3.32(0.23)	-2.81
HE 2344-2800	-135.8	-3.06(0.20)	-2.53
HE 0024-2523 <sup>d</sup>	-181.6	-3.08(0.24)	-2.62
HE 0130-2303	+74.2	-3.15(0.19)	-2.93
HE 0132-2439	+294.7	-3.05(0.33)	-3.56
HE 0148-2611	-223.1	-3.42(0.17)	-2.96
HE 0218-2738 <sup>e</sup>	+134.0	-3.81(0.17)	-3.52
HE 0242-0732	-188.9	-3.59(0.20)	-3.04

<sup>a</sup>These values are inferred from the strength of the Ca II K line and the Balmer lines in the moderate-resolution spectra. There is a small systematic offset of 0.23 dex between the abundance scales of the followup spectra and of the high resolution spectra. See the text for details.

<sup>b</sup>[Fe/H] values are from the detailed abundance analysis presented in Paper II.

<sup>c</sup>The uncertainty in the radial velocities is dominated by systematic errors, and is  $\pm 1.0$  km s<sup>-1</sup>.

<sup>d</sup>This star has easily detectable CH absorption in the G band and its lines are resolved.

<sup>e</sup>The HIRES spectra show this star is a double-lined spectroscopic binary.

<sup>f</sup>This is the heliocentric radial velocity.



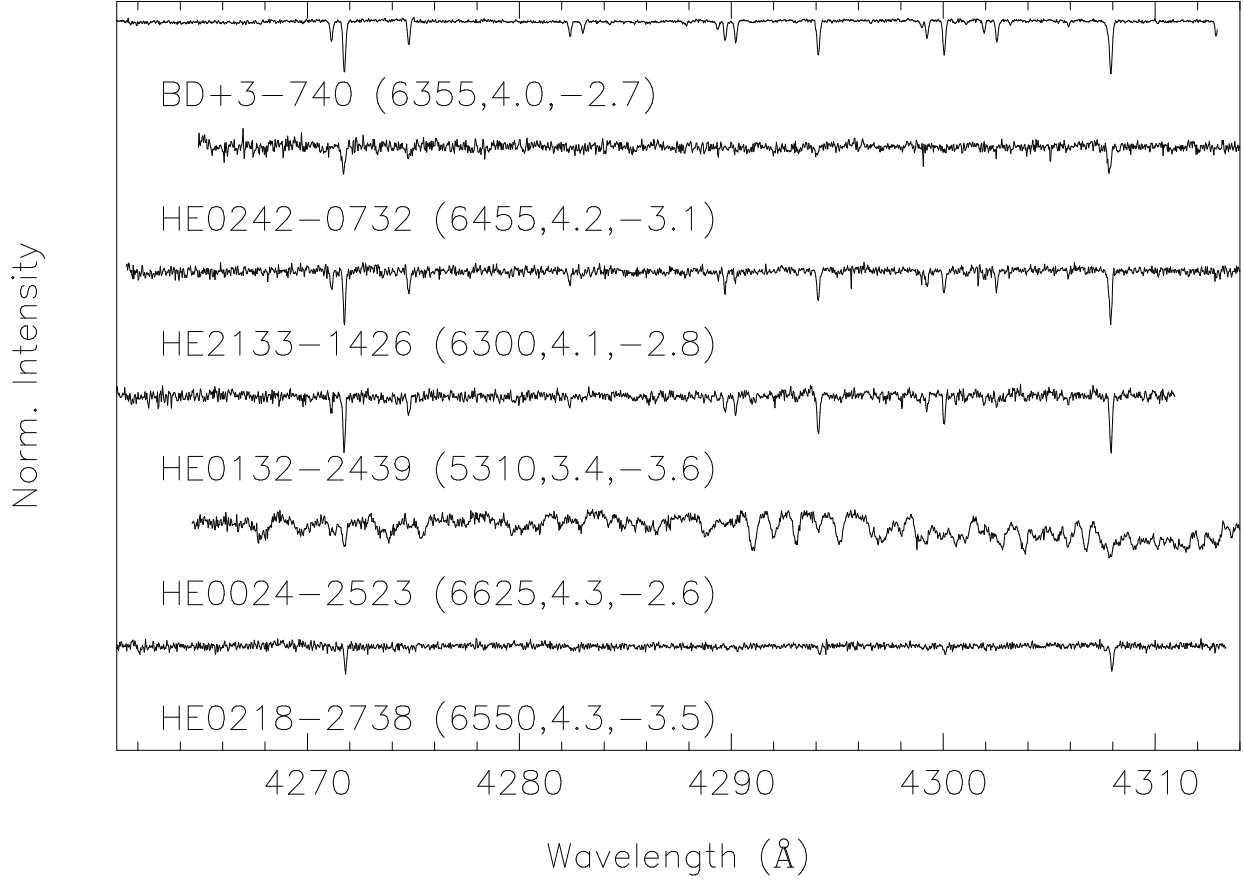


Fig. 1.— The HRES order containing the G band of CH is shown for six stars. BD+3 740 is a bright calibrating main sequence star; HE 0242–0732 is also a turnoff star, as is HE 2133–1426, the faintest star in the present sample. HE 0132–2439 is the only giant from the HES in our sample. HE 0024–2523 is the only star which shows easily detectable CH and its lines are resolved. HE 0218–2738 was found to be a double-lined spectroscopic binary. The spectra have been shifted in wavelength to remove the effects of the difference in radial velocities among these stars.

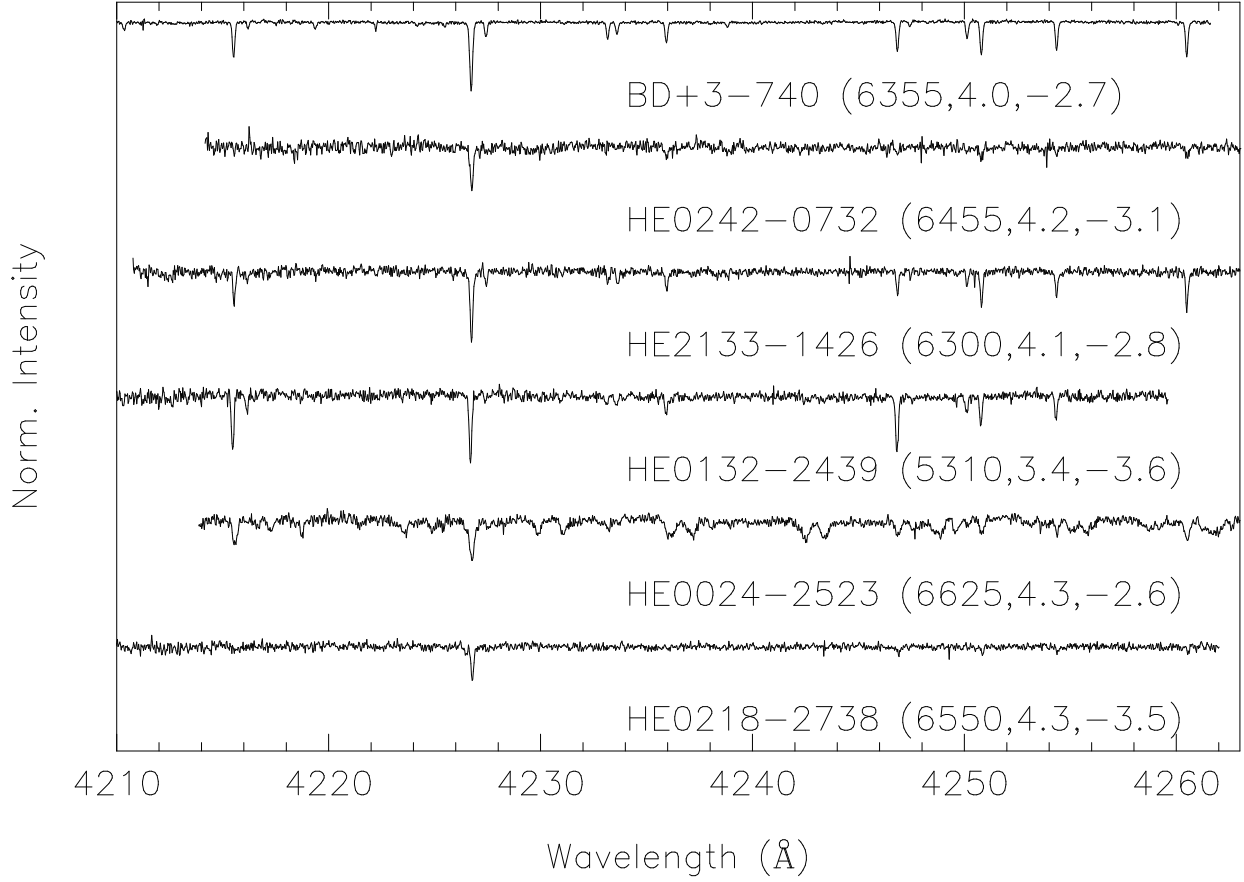


Fig. 2.— The spectra of the same six stars are shown in the region of the SrII line at 4215.5 Å. The strongest line in this order is the CaI absorption line at 4226.7 Å. The broader lines found in the spectrum of HE 0024–2523 are apparent here. The spectra have been shifted in wavelength to remove the effects of the difference in radial velocities among these stars.

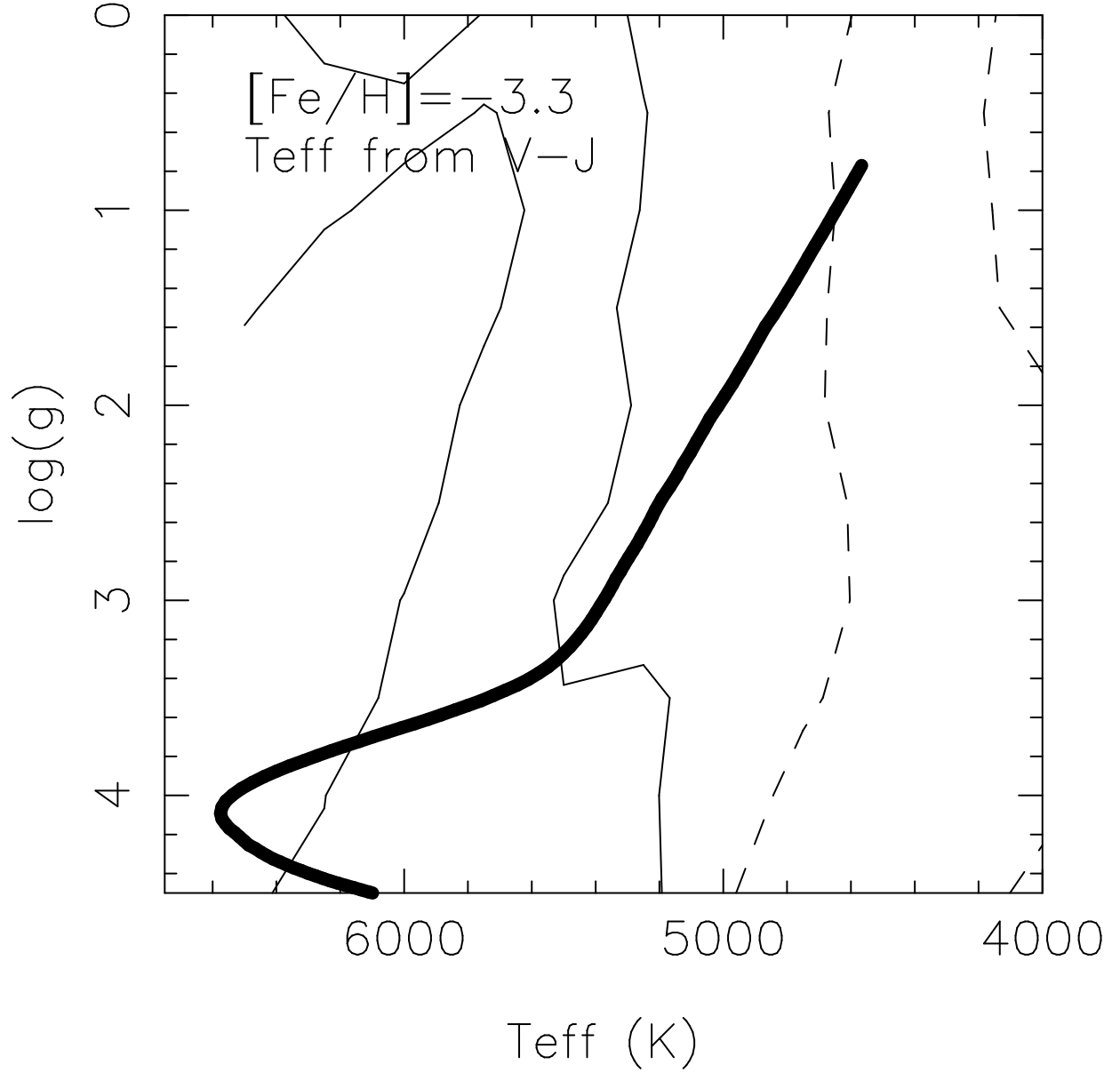


Fig. 3.— A comparison of the Kurucz and MARCS temperature scale from  $V - J$  colors. The four contour levels shown correspond to  $\Delta T_{\text{eff}} = -30, -10, 10$  and  $30$  K. The thick curve is a 12 Gyr isochrone for a very metal poor star from the very recently completed  $Y^2$  grid of isochrones of Yi *et al.* (2001).

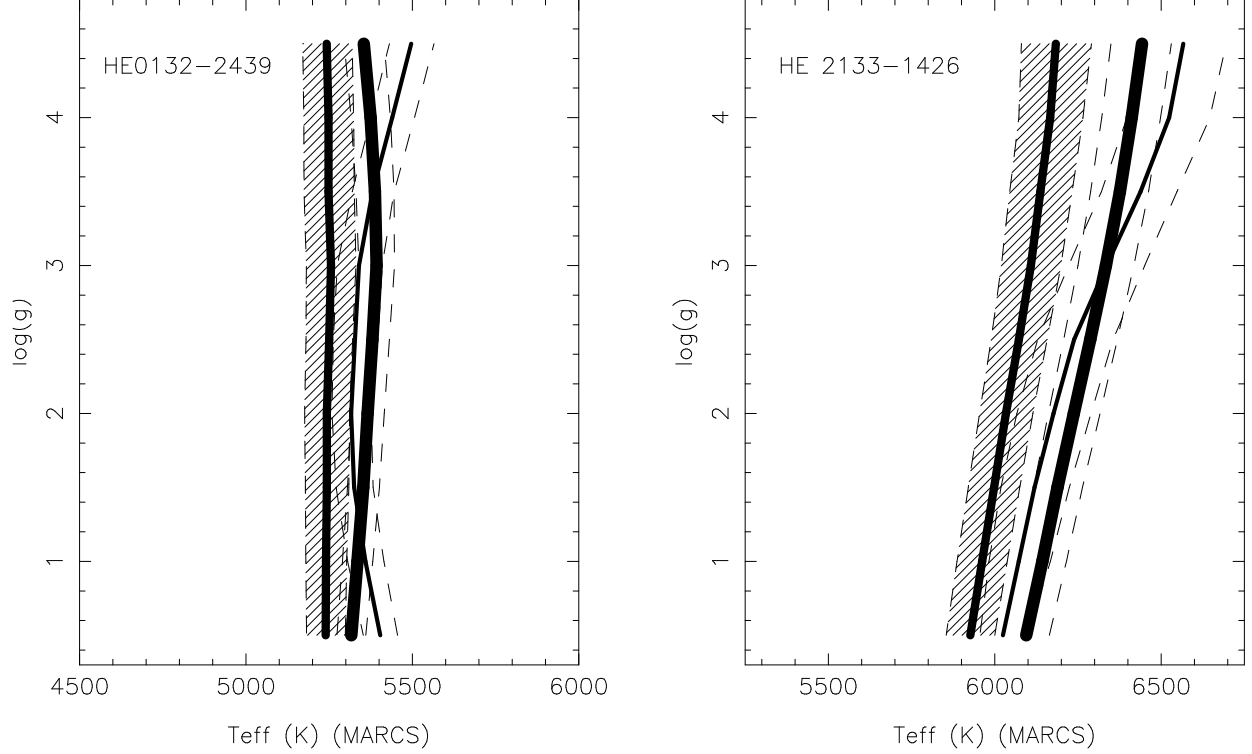


Fig. 4.— Examples of our procedure for deriving  $T_{\text{eff}}$  from stars in our sample are shown. The left panel is for the star HE 0132-2439, an EMP giant. The solution for its  $T_{\text{eff}}$  from its dereddened colors is displayed as a function of  $\log(g)$  with  $[\text{Fe}/\text{H}]$  assumed to be  $-3.0$  dex. The results from the  $B - V$  measurement are shown as the thinnest solid curve, from the  $V - J$  color as thicker solid curve, and from the  $V - K$  color as the thickest solid curve. Dashed curves denote the values of  $T_{\text{eff}}$  inferred from the measured and dereddened colors  $\pm$  their  $1\sigma$  uncertainties. The striped area indicates that allowed within this  $1\sigma$  uncertainty level inferred from the  $V - J$  color. In the second panel, we show the  $T_{\text{eff}}$  determination for the faintest star in the present sample, HE 2133-1426, a EMP star near the main sequence turnoff.

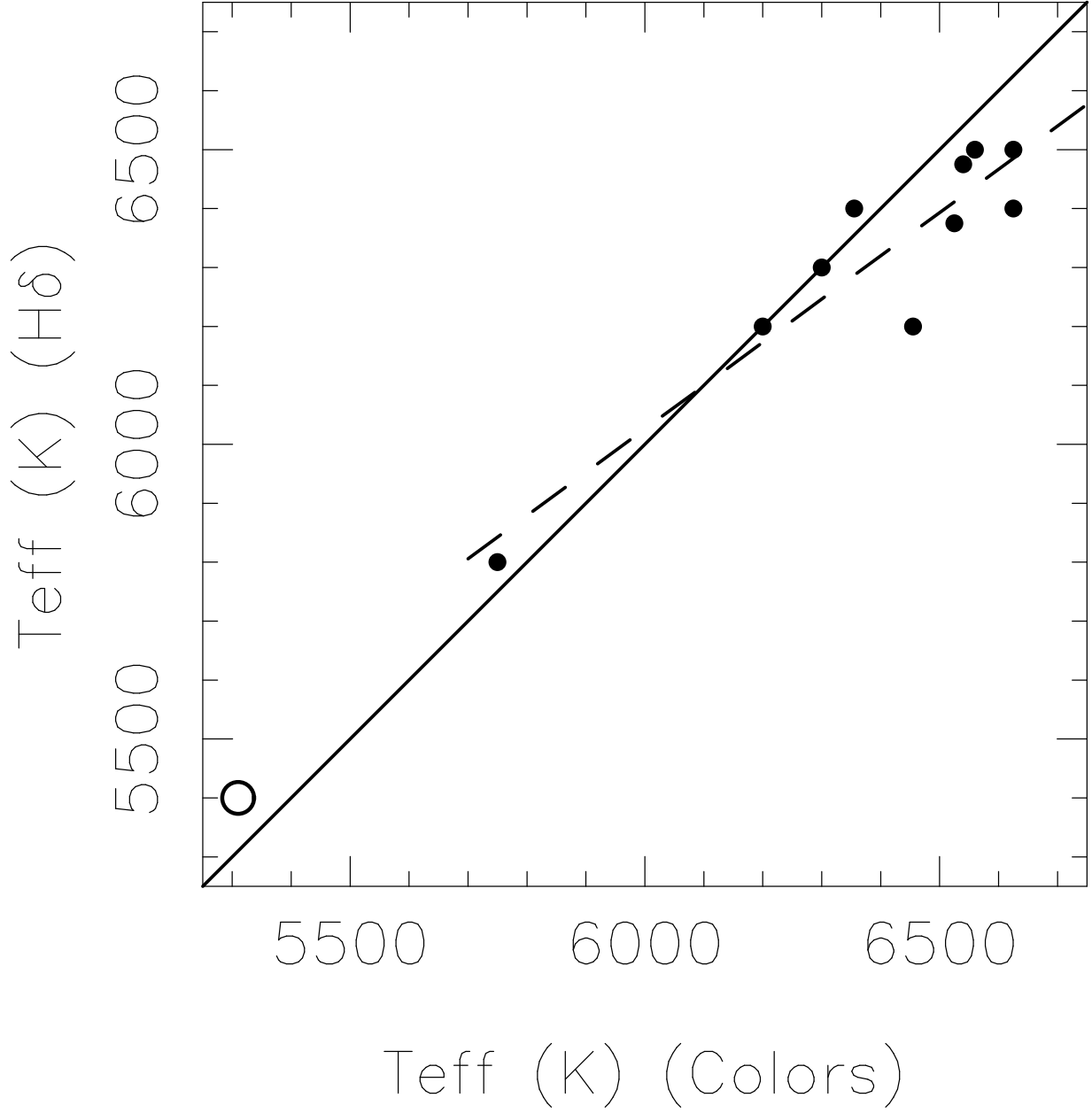


Fig. 5.— The  $T_{\text{eff}}$  values deduced from the analysis of the profiles of the  $\text{H}\delta$  lines in our sample of very metal poor stars is shown as a function of the  $T_{\text{eff}}$  values derived from the observed, dereddened colors. The solid line denotes equality, while the dashed line indicates the best linear fit. The large open circle denotes the only subgiant in our present sample, which is not included in the fit. The  $\sigma$  about the best fit line is  $\sim 75$  K.